Upwelling induced variability of chlorophyll in the Taiwan Strait as observed by SeaWiFS and AVHRR

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ABSTRACT

SeaWiFS SeaWiFS Chl and AVHRR SST time-series in August, 1998 were used to evaluate short-term variability of Chl associated with upwelling events in the western Taiwan Strait. Extents of eutrophic waters(SeaWiFS Chlorophyll >1mg/m^3) and extents of colder than non-upwelling waters were calculated for the western strait and for the north and south portions, respectively. High extents of eutrophic waters were always accompanied by high extents of colder than nonupwelling waters, indicative of tight coupling of Chl with SST evolution and thus with upwelling activities. Only one-day lag of phytoplankton growth to upwelling was detected. The temporal patterns of upwelling events were found different in the northwestern and southwestern Taiwan Strait. In the north portion, a short relaxation of upwelling probably occurred between early and mid-August. One unique strong upwelling event was likely going from early through mid-August, peaking before Aug.13th in the south portion. It resulted in chlorophyll enhancement developing and reaching peaks not concurrently in these two upwelling zones. The duration of one upwelling event in the western Taiwan Strait in August was estimated to be ca.12days. Two distinctive upwelling systems located in the northwestern and southwestern Taiwan Strait were further inferred.

Keywords: Upwelling events; Chlorophyll; Short-term variability; Remote Sensing; AVHRR; SeaWiFS, Taiwan Strait, China

1 INTRODUCTION

Coastal upwelling ecosystems, for example, those off Peru[1], off California[2], are always like under spotlight owing to its cold, nutritious and productive features and thus its contribution to ocean productivity and fishery. Upwelling is nevertheless periodic inducing pulse input of nutrients to the surface water. Therefore in situ survey will probably miss some events, especially the periodicity of upwelling and the ecological response due to the limitation of shipping time. Remote sensing has the advantage of synopticity and repetitive coverage so that it has been approved to be a very useful tool to discover the upwelling waters[3], to observe the size of upwelling ecosystems[4], move of cold water centroid[5], and the inter-annual variability of phytoplankton standing crop and its connection with El Nino[6].

However, ecological responses to the periodic upwelling events seems having not been so frequently reported due to the short of time-series data. For example, Takahashi et al.[7] had ever observed daily changes in nutrient concentrations and phytoplankton biomass during an upwelling event around the Izu Peninsula, Japan; the observation only covered a period of 6 days. Kudela et al.[8]once reported phytoplankton carbon and nitrogen uptake response to light change caused by an upwelling event in Monterey Bay; the upwelled water was tracked over a period of 5 days using a holey-sock drifter.

Fortunately remote sensing sensors well utilized by oceanographers recently, the Sea Wide Imaging Field Sensor(SeaWiFS) and the Advanced Very High Resolution Radiometer (AVHRR) provide us a high resolution time-series of surface Chlorophyll a(Chl) and Sea Surface Temperature(SST) data in August, 1998 in the region of Taiwan Strait. This dataset enables us to have a look at the Chl temporal pattern related to upwelling events.

Taiwan Strait(Fig.1) is a shallow shelf channel linking the East China Sea(ECS) and the South China Sea(SCS) characterized by seasonal and year-round upwellings[9,10]. Taiwan Bank is the most shallow in the whole region, with water depth varying from 10 to 30m. Northeast monsoon prevails during winter, while winds are predominantly southwesterlies in summer. Under the forcing of monsoon, different waters coming from the ECS and SCS enter this region in different seasons[11,12,13]. As a consequence, the northern Taiwan Strait and the southern Taiwan Strait exhibit different physical and biogeochemical structures[14]. During summer monsoon, warm South China Sea Water covers the whole region. However alongshore winds induce coastal upwelling in the western strait offshore mainland. In the vicinity of Taiwan Bank upwelling develops as well. Thus cold waters influence broader areas in the southern region than in the northern portion[9,10,15]. Hence in the northern Taiwan Strait, phytoplankton bloom generally occurs during inter-monsoon(Spring and Autumn), when there are plenty of nutrients providing by the ECS coastal water and the temperature and radiation are well situated for phytoplankton growth; in the southern Taiwan Strait, Chlorophyll a reaches its peak only in summer[16]. Recently, Tang et al.[17] investigated the upwelling in the Taiwan Strait with AVHRR SST and SeaWiFS Chl data, and reported the size and intensity of those upwelling zones. As to the chlorophyll a variation at daily scale, especially concerning the response to upwelling events, it is absolutely blank in this region.

Our focus in this paper is to evaluate the Chl response to upwelling events. We restrict the study region to the western Taiwan Strait to do evaluation on the satellite time-series data, where summer monsoon induces coastal upwelling. The results of Chl and SST short-term variation derived from the daily imageries of SeaWiFS and AVHRR will be presented and discussed.

2 DATA AND METHODS

SST imageries of AVHRR was obtained from the Second Institute of Oceanography, State Ocean Administration of China. MCSST algorithm was chosen to derive SST products from L1 data.

SeaWiFS L1 data, and ancillary ozone and meteorological data, were acquired from NASA Goddard Space Flight Center. SeaDAS 4.0 was used to generate L3 imagery from L1 data. A multi-scattering with 765/865 Gordon- Wang model was used for atmospheric correction and OC4 algorithm was used for retrieving Chl. Mercator projection was chosen for mapping.

We did evaluation on time-series Chl and SST in a grid of two sub-areas. The study region was defined generally by geological middle-line of the Taiwan Strait and then was further divided into two zones separating the north zone(N) from the south zone(S)(Fig.1).

In order to evaluate the temporal change of Chl, we followed the algorithm of Kahru and Mitchell[6], calculating the areal extent of eutrophic waters. Pixels with Chl greater than 1.0mg/m^3 were classified as eutrophic water.

For each of the AVHRR images, we calculated the mean SST in the lower left area bounded by 22.00°N116.26°E ~21.50°N120.00°E, as representative of nonupwelling water. And then for Zone S and Zone N as indicated in Fig.1, we calculated the areal extent of waters colder than the nonupwelling water by 2°C, as a proxy for the area influenced by upwelling.

3 RESULTS

3.1 Temporal pattern of Chl

It was straightforward that waters with high Chl contents in the western Taiwan Strait changed their areas with time(Fig.2). The variability would be well demonstrated by calculating the areal extent of eutrophic waters for the study region located in the western Taiwan Strait(Fig.3a). The extent of eutrophic water was higher in mid-August than the previous or subsequent days, peaking on the 13th. When approaching late August, the eutrophic water lowered its extent obviously. We haven't seen very large daily variation, yet within three days, for example, from Aug.11th to the 13th, the extent of eutrophic waters increased ca. 15%. From Aug.18th to the 23rd, 40% drop of the extent of eutrophic waters was detected and continually decreased to the minimal on the 26th. However, on the next day it gained a sudden recovery of more than 100% extent. Because on the time-series we miss at most 5 days between each two records due to cloud-cover, it was nevertheless rather a guess that the extent of eutrophic water kept high through early to mid-August but had dropped a lot in late August. This would be left for further discussion in Section 4.

There seemed zonal differences of the pattern if we did calculation on the southwestern(Zone S) and the northwestern zone(Zone N) separately(Fig.3b). The maximum extent of eutrophic water appeared in Zone S on Aug.13th, which resulted of the peak of the extent of eutrophic water for the whole study region. In Zone N maximum occurred on the 7th and there was a less strong peak occurring on the 16th. For Zone S, from the 11th to the 15th, the extent of eutrophic waters varied quickly, rising up and then dropping down 30% within 5 days. For Zone N, relatively gradual increase of the extent of eutrophic waters was found during this period. When approaching late-August it had decreased nearly one times comparing to the previous days for Zone N and only 30% decreased for Zone S. One more distinct feature was that the maximum of Zone S was higher than that of Zone N. And this was why the temporal pattern of the whole region was almost determined by the pattern of Zone S.

3.2 Temporal pattern of SST

As the AVHRR SST images indicated, SST distribution pattern experienced rapid changes, too(Fig.4). It was obvious that the areas with SST colder than 27°C appeared highly variable. As a measure of the area influenced by upwelling, we calculated the areal extent of waters colder than the nonupwelling waters by 2°C (Fig.5). For Zone S, maximum extent of colder than nonupwelling waters appeared on the 7th, and then lost 30% of the strength on the 15th. On the 17th, it had decreased to less than half of the maximum extent. For Zone N, the extent of colder than nonupwelling waters on the 15th was as high as that on the 7th, and then decreased gradually. On the 17th, it had reduced solely a little bit more than 20% of the maximum extent. As to late-August, both of the zones exhibited low extents of colder than noupwelling waters. And both of them had a recovery on the 26th. The differentiation was that the recovery for Zone S was three times of that for Zone N.

4 DISCUSSION

4.1 Coupling of Chl variability with SST

Comparing the extent of eutrophic waters(Fig.3) with the extent of colder than nonupwelling waters(Fig.5), we would find tight relationships between Chl and SST as expected, and as other earlier and recent works with Coastal Zone Color Scanner(CZCS), Ocean Color and Temperature Scanner(OCTS) and SeaWiFS imagery illustrated[18,19,20]. Extension of high Chl waters was accompanying with the coming of cold waters, that was consistent with the concept that upwelling provided cold deep waters with plenty of nutrients to the surface water, resulted in Chl enhancement. To facilitate comparison, we combined the Chl and SST datasets(to be simplified, hereafter C and T), which were the extent of eutrophic waters and the extent of colder than nonupwelling waters(Fig.6). It was easy to notify two groups of Chl and SST pairs, one of high C and high T and the other of low C and low T, except in Fig.6(c). It was related to the period of the early and mid-August on contrast to the late August. Both C and T was one times lowered in the latter period than in the former period. The exception appeared in Zone S(Fig.6(c)) was attributed to one data point occurring on Aug.26th, when high T did not correspond to high T. This would be reasonable if we noticed that it was a switch day when T increased from the minimal of the 25th(Fig.5). The phytoplankton response to the nutrient input arisen by upwelling would not be so prompt as reported by Takahashi et al.[7]. They found maximum ratio of Chlorophyll a in total pigments and phytoplankton growth rate were reached one day after the highest nutrient and lowest SST were observed. We also found recovery of the extent of eutrophic water on Aug.27th following the increase of the extent of colder than nonupwelling water on the 26th(Fig.3 and Fig.5). Hence one-day lag of phytoplankton growth to upwelling appeared true in the Taiwan Strait.

4.2 Temporal pattern of upwelling events

As we have mentioned above, the coastal upwelling was forced by southwesterly wind. The wind speed and direction observed at PingTan island from July to August, 1998 were shown in Fig.7. Strong southwesterly wind persisted from July 15th to August 19th, while wind changed its direction for about three days from August 2nd to the 5th. However the strength of southwesterly wind from Aug.6th to the 19th had been reduced compared to that from July 15th to Aug.1st. After Aug.19th, weakened southwesterly wind occurred only in the period from the 23rd to the 27th.

We have detected enhanced Chl in Zone N early on Aug.2nd. On Aug.7th, SST was low and Chl was high. However, on Aug.8th, from the AVHRR SST image(not shown here due to the cloud cover in the southern Taiwan Strait), we found that the water colder than 26°C had nearly disappeared in Zone N. This would be understandable by noticing that wind was not favorable for upwelling from Aug.2nd to the 5th. From Aug.11th to the 18th, Chl was high. Cold water extents were high from the 15th to the 17th but was slightly decreasing, because the wind was not so strong as in July. From the 23rd to the 25th, upwelling had significantly weakened, while slight recovery of upwelling intensity occurred on the 26th. Variable wind direction after the 19th was conducive to this relaxation of upwelling. Therefore there would be three stages of coastal upwelling in the northern region in August. A strong upwelling event occurred in early August, which was followed by a less strong one going on in mid-August. In late August, no strong upwelling events formed. That is to say, the duration of one upwelling event in mid-August was between 7 and 12days, which was not well agreed with the result of Hu and Chen[21] by doing statistical analysis on the data derived from a numerical model, though their study targeted solely at the southern Taiwan Strait. We would estimate much more than 14days coastal upwelling through June to August in the northern Taiwan Strait, in contrast to their estimation of 15days of upwelling during the entire summer.

4.3 Potential different upwelling systems in the northwestern and southwestern Taiwan Strait

The temporal pattern of upwelling events for Zone S would be different from that for Zone N based on the finding that there were evident differences between them in the patterns of Chl and SST evolution. For Zone N, there were two peaks of extent of eutrophic waters appeared, first on the 7^{th}, the second on 16^{th}; For Zone S, only one peak shown on the 13^{th}. The upwelling in Zone S looked not ceasing on Aug.8^{th} as also suggested by the partly cloud covered AVHRR SST image on that day(not shown). It probably kept strengthening after 7^{th} and thus induced the Chl peak on the 13^{th}. The lowest *in situ* SST observed along the southern coast on the 11^{th} was ca.23.5°C, which was more than 1°C lower than the lowest SST observed along the northern coast on the 15^{th}, indicative of rather strong upwelling in Zone S on Aug.11^{th}. In a word, there seemed only two stages of upwelling in Zone S. The strong one was from early August through mid-August; a weak one was in late August. Non-uniform of wind stresses over the strait was thought to be one of the reasons causing the differences in upwelling temporal patterns between the northern and the southern regions, though we haven't been able to prove it currently without a full record of wind field in the whole Taiwan Strait during this period. We inferred that the northern and southern upwelling would likely be related to the East China Sea and the South China Sea coastal upwelling systems respectively. It was actually straightforward on the AVHRR SST images(Fig.4) that cold waters in the northwestern strait and the southwestern strait were blocked by relatively warm waters in between most of the time, and the cold water in the northwestern strait was connected to the cold water along East China Sea coast. Huang et al.[14] had reported the differences in the size fractionated structure of phytoplankton for the northern and southern Taiwan Strait. The northern Taiwan Strait appeared more or less one part of East China Sea and the southern Taiwan Strait exhibited the features of South China Sea more. Therefore, the Taiwan Strait would be playing a significant role in the matter exchange between the South China Sea and the East China Sea.

5 SUMMARY

SeaWiFS Chl and AVHRR SST time-series in August, 1998 were used to evaluate short-term variability of Chl associated with upwelling events in the western Taiwan Strait. Highly variable Chl patterns were found. Chl may rise up 30% and then drop down 30% within five days. High extents of eutrophic waters were always accompanied by high extents of colder than nonupwelling waters, indicative of tight coupling of Chl with SST evolution and thus with upwelling activities. Only one-day lag of phytoplankton growth to upwelling was detected.

The temporal patterns of upwelling events were found different in the northwestern and southwestern Taiwan Strait. Though upwelling in both regions was weak in strength while approaching late August, a short relaxation of upwelling probably occurred between early and mid-August in the north portion. In the south portion, one strong upwelling event was likely going from early through mid-August, peaking before Aug.13^{th}. The duration of upwelling events in the western Taiwan Strait in August would thus be estimated to be ca.12days. Two distinctive upwelling systems located in the northwestern and southwestern Taiwan Strait were further inferred, hinting the northern and the southern Taiwan Strait were related to the East China Sea and the South China Sea respectively. The Taiwan Strait may play a remarkable role in matter exchange between the East China Sea and the South China Sea in this sense.

With the help of remote sensing data, for the first time we observed the temporal and spatial features of coastal upwelling events and its associated chlorophyll responses in the Taiwan Strait. However we should keep in mind that the wind data used here was based on the observation done at two islands, and time-series satellite data was actually not continuous time-series. Understanding short-term evolution of physical and biological processes requires drawing upon the strengths of the in situ buoy monitoring, underway mapping and satellite observation in combination.

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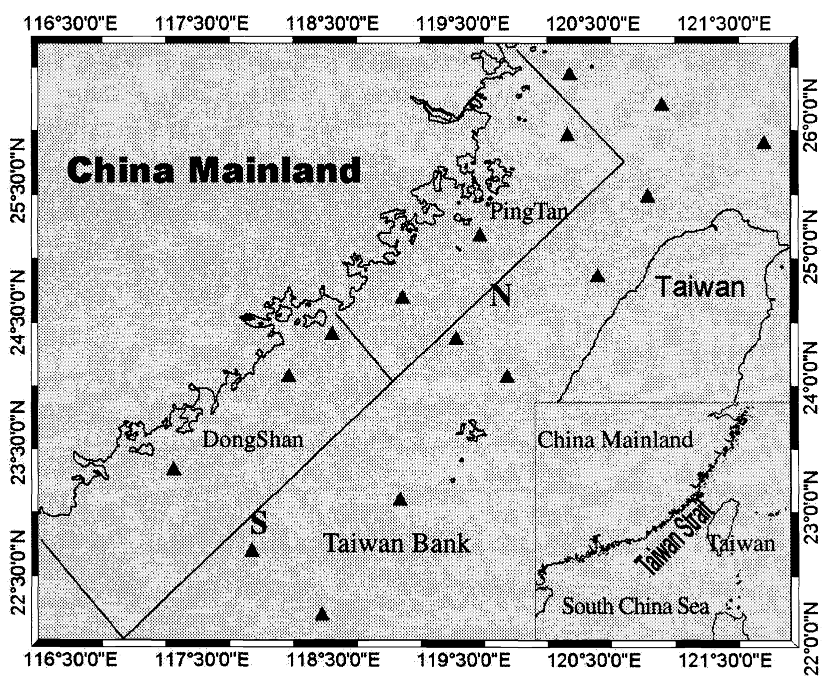

Fig.1 Map of the study region with the grid of two sub-areas, forming zones of southwestern Taiwan Strait(S) and northwestern Taiwan Strait(N), while triangles denote CTD and fluorometer sampling stations in the 1998 summer cruise

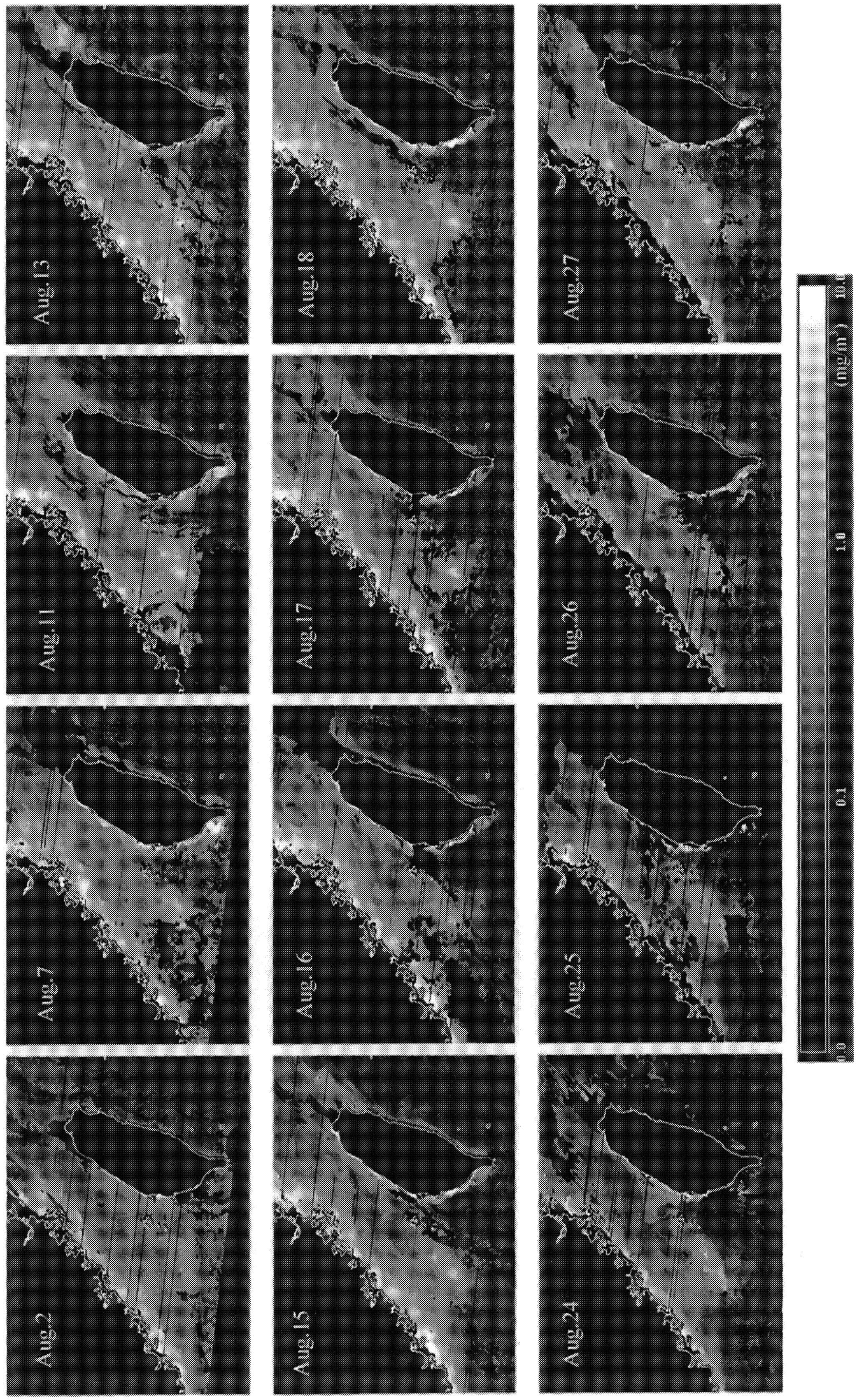

Fig.2 SeaWiFS Chl daily images of the Taiwan Strait region in August, 1998

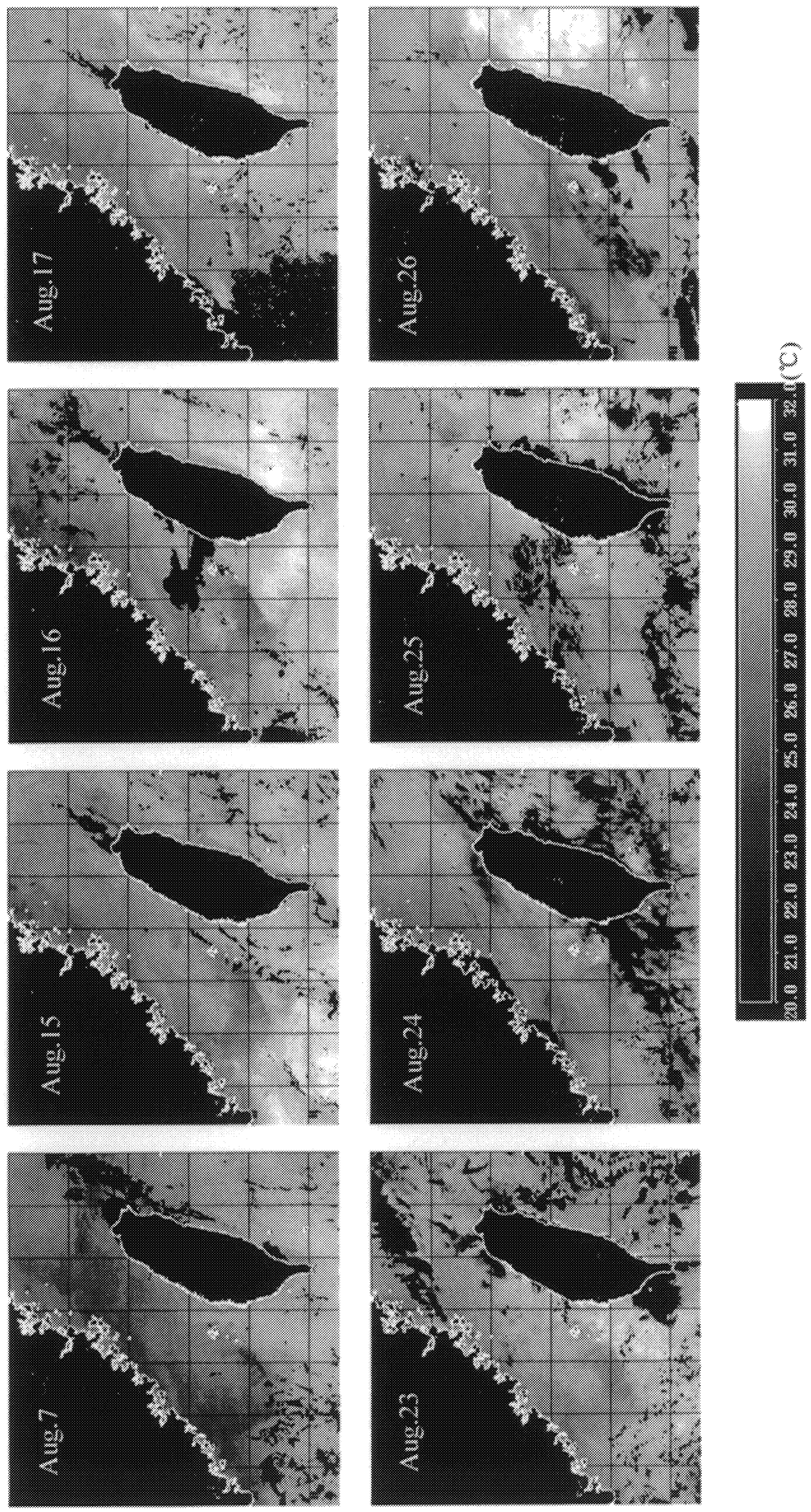

Fig.4 AVHRR SST daily images of the Taiwan Strait region in August, 1998

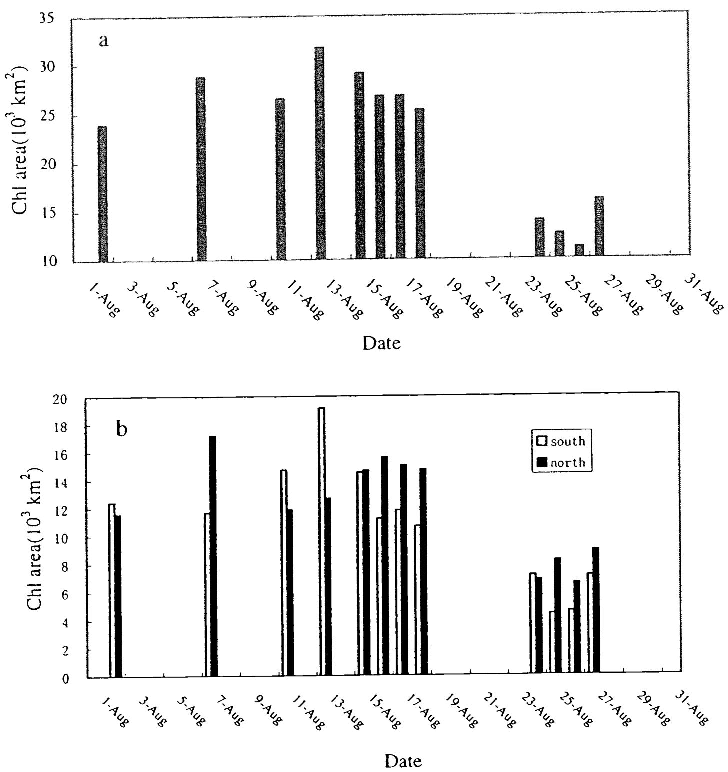

Fig.3 Time series of the areal extent of eutrophic waters in August, 1998 (a) in the western Taiwan Strait; (b) in the southwestern(Zone S) and northwestern Taiwan Strait(Zone N) separately.

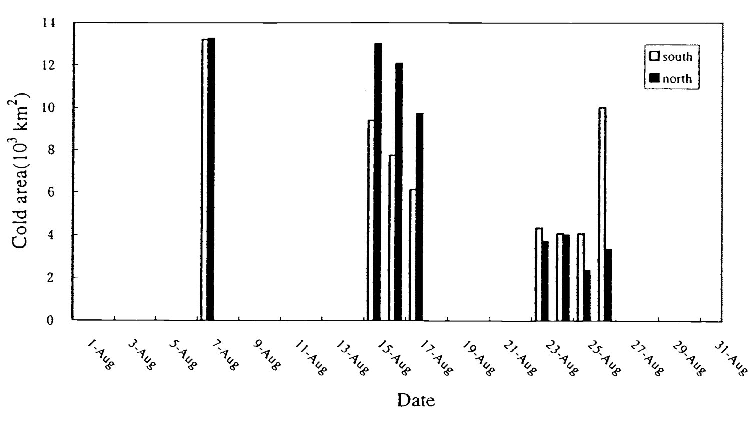

Fig.5 Time series of the areal extent of colder than non-upwelling waters in August, 1998 (a) in the western Taiwan Strait; (b) in the southwestern(Zone S) and northwestern Taiwan Strait(Zone N) separately.

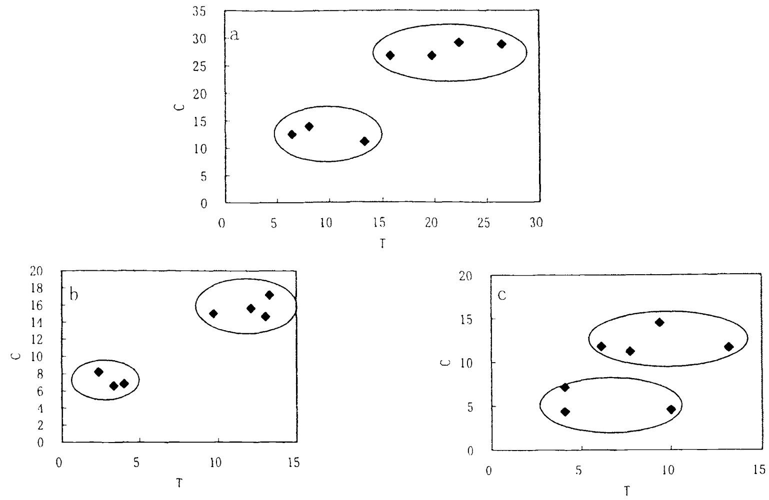

Fig.6 Diagrams of the extent of eutrophic waters versus the extent of colder than non-upwelling waters. C was a simplified expression of the extent of eutrophic waters($10^3 km^2$), T was a simplified expression of the extent of colder than non-upwelling waters($10^3 km^2$). (a) the western Taiwan Strait; (b) the northwestern(Zone N) Taiwan Strait; (c) the southwestern Taiwan Strait(Zone S).

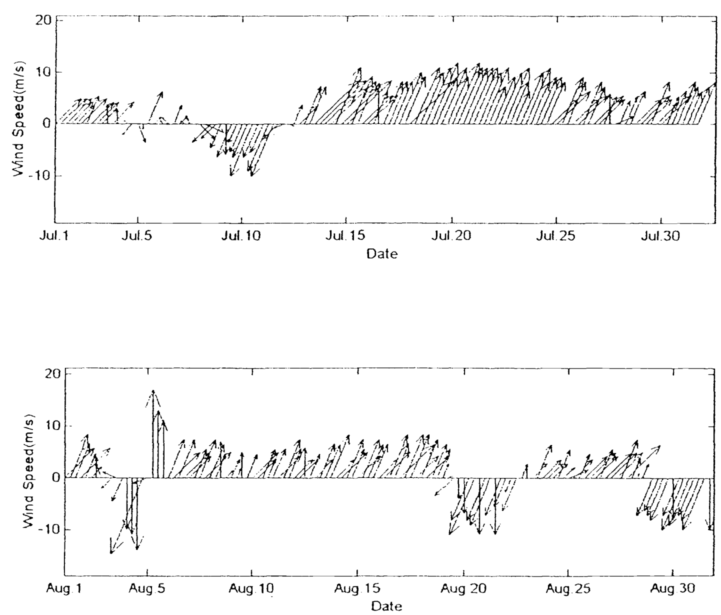

Fig.7 Stick diagram of wind velocity from July to August, 1998 at a weather station on PingTan Island.